

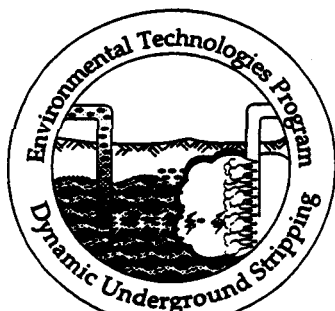
## Summary of the LLNL Gasoline Spill Demonstration— Dynamic Underground Stripping Project

R. L. Newmark and R. D. Aines

April 3, 1995



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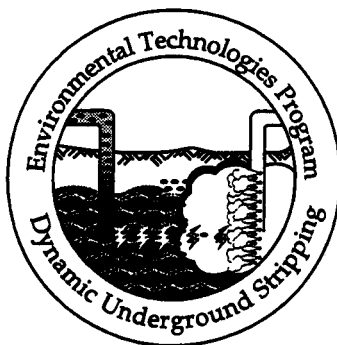
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## **Summary of the LLNL Gasoline Spill Demonstration— Dynamic Underground Stripping Project**

**R. L. Newmark and R. D. Aines  
Environmental Technologies Program**



**UCRL-ID-120416**



## Preface

This report summarizes the four volumes of *Dynamic Underground Stripping Project: LLNL Gasoline Spill Demonstration Report* (Newmark, 1994a), which compiles the final reports for all the component activities of the Dynamic Underground Stripping demonstration at the LLNL gasoline spill site. The demonstration and cleanup efforts at that site from 1992 to early 1994 were funded jointly by the Department of Energy's Office of Technology Development and Office of Environmental Restoration. The full report combines those efforts into sections that reflect the major technical aspects of the project: Summary, Characterization, Operations, Monitoring, Predictive Modeling, and the Accelerated Removal and Validation (ARV) Project.

The Dynamic Underground Stripping demonstration at the LLNL gasoline spill site was extremely successful, and all of the project goals were met or exceeded. All aspects of this project reflect the integration of complementary technologies and process engineering. Some applications are obvious, such as the use of electrical heating and steam injection to heat the whole range of soil types. Others are not so obvious, such as the need to electrically isolate diagnostic and monitoring systems from the tremendous currents intentionally applied to the ground. The technical challenges in merely fielding these methods in a safe and effective manner at an operating industrial site were great. Safety in operation was a prime design parameter; our excellent safety record is one of the most satisfying accomplishments of this project. The combined achievements are greater than the sum of each individual component; this satisfies the requirements of true integration of method and application.

## Acknowledgments

The full report, like the demonstration project itself, represents collaboration among investigators from many organizations, both between LLNL and other agencies and between organizations within LLNL. In particular, we acknowledge the contributions of Professor Kent Udell and the team members from the Environmental Restoration Center of the University of California at Berkeley, and the close collaboration between these individuals and LLNL researchers. The success of this project was largely due to the unique field-scale collaboration that utilized the complementary interests and research abilities of University and Laboratory researchers.

The successful demonstration of Dynamic Underground Stripping at the LLNL gasoline spill site was made possible through the combined efforts of a great many people, with a broad range of expertise. We acknowledge the efforts of the mechanical and environmental technicians, procurement, construction and plant engineering personnel, and other staff without whose contributions (often in difficult conditions and inclement weather) this project would not have been possible. Students from the Environmental Center at University of California-Berkeley also provided essential support.

We gratefully acknowledge the support of the U.S. Department of Energy's Office of Environmental Management for this demonstration. The demonstration of innovative technologies requires that both experimental and compliance-driven cleanup operations needs be addressed. The efforts of the U.S. Department of Energy's representatives to reconcile often conflicting requirements made this project possible. In particular, we acknowledge the efforts of Clyde Frank, Pat Whitfield, Tom Crandall, Tom Anderson, Katie Hain, John Mathur, Kathy Angleberger, John Lehr, J. T. Davis, Richard Scott, Mike Brown and Bill Holman. Over its three-year history, this project utilized the resources of many, if not most, of the organizations at LLNL. In particular, we acknowledge the support of Jesse Yow, John Ziagos, Lee Younker, Bob Schock, J. I. Davis, Ann Heywood, Jay C. Davis, Alan Levy, Walt Sooy, Dennis Fisher, Harry Galles, Jens Mahler, and Bill McConachie.

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# Summary of the LLNL Gasoline Spill Demonstration— Dynamic Underground Stripping Project

## Introduction

Underground spills of volatile hydrocarbons (solvents or fuels) can be difficult to clean up when the hydrocarbons are present both above and below the water table and are found in relatively impermeable clays (Figure 1). Years of groundwater pumping may not completely remove the contamination. Researchers at Lawrence Livermore National Laboratory (LLNL) and the College of Engineering at the University of California at Berkeley (UCB) have collaborated to develop a technique called Dynamic Underground Stripping to remove localized underground spills in a relatively short time. The U.S. Department of Energy's Office of Environmental Restoration and Waste Management has sponsored a full-scale demonstration of this technique at the LLNL gasoline spill site.

Although it has been known for years that accumulations of separate-phase organics represent the most serious cause of groundwater pollution (National Research Council, 1994; MacDonald and Kavanaugh, 1994), their very low solubility in water has made them very hard to remove by the classic method of pumping out groundwater and treating it at the surface. Similarly, the principal natural mechanism for groundwater restoration, biological metabolism of the contaminant, usually will not work in very concentrated contaminant because of the toxic nature of the organic. (Bacteria typically metabolize organics dissolved in water, not free organic liquids.)

When highly concentrated contamination is found above the standing water table, vacuum extraction has been very effective at both removing the contaminant and enhancing biological remediation through the addition of oxygen. Below the water table, however, these advantages cannot be obtained. For such sites where the contamination is too deep for excavation, there are currently no widely applicable cleanup methods.

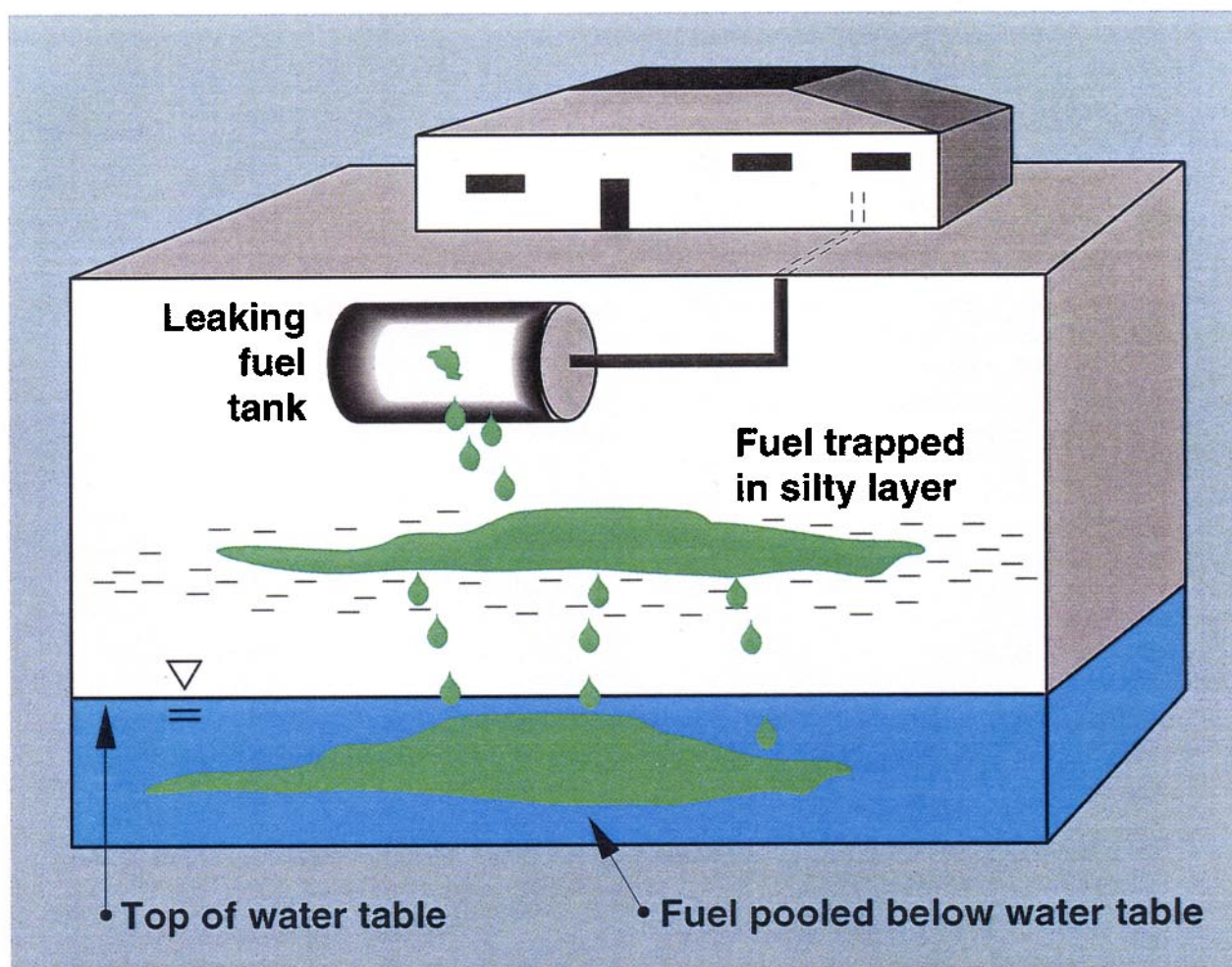
Dynamic Underground Stripping removes separate-phase organic contaminants below the water table by heating the subsurface above the boiling point of water, and then removing both contaminant and water by vacuum extraction. The high temperatures both convert the organic

to vapor and enhance other removal paths by increasing diffusion and eliminating sorption. Because this method uses rapid, high-energy techniques in cleaning the soil, it requires an integrated system of underground monitoring and imaging methods to control and evaluate the process in real time.

## Results of First Full-Scale Test

We conducted the initial testing of the combined thermal and monitoring/imaging methods of Dynamic Underground Stripping at the site of a gasoline spill at the Lawrence Livermore National Laboratory. This site was chosen because several thousand gallons of gasoline were trapped up to 30 feet below the water table (Figure 2), mimicking the behavior of heavy solvents such as trichloroethylene (TCE).

This first full-scale test of Dynamic Underground Stripping at the LLNL gasoline site was extremely successful. Results completed in December 1993 indicate that the process is more than 60 times as effective as the conventional pump-and-treat process now being used at 300 designated Superfund Sites to treat contamination below the water table, and is 15 times as effective as vacuum extraction in the vadose zone (above the water table) (Figure 3). The LLNL site was previously under treatment by vacuum extraction from a central extraction well (Nicholls et al., 1988; Thorpe et al., 1990; Cook et al., 1991). From August 1988 to December 1991, more than 1900 gallons of gasoline were removed from the vadose zone. However, the extraction rate had dropped to about 2 gallons per day by 1991. No large groundwater removal actions were undertaken at that point; but because of the low solubility of gasoline in water (about 10,000-ppb total hydrocarbons were observed in the groundwater), a pumping rate of 50 gallons/minute would have only removed about 0.5 gallon of gasoline per day. To continue the cleanup, the vacuum venting operation was halted, and replaced by the Dynamic Underground Stripping technique.



**Figure 1.** A plume of organic liquid forming beneath a leaking underground storage tank. This behavior is typical of a heavy organic solvent such as trichloroethylene (TCE). Some of the liquid may be trapped in layers of low-permeability soil above the water table. The remainder will form a pool below the water table, as shown here. Lighter contaminants such as gasoline can be trapped below water by movement of the water table.

During the 21 weeks of operation over the course of one year, Dynamic Underground Stripping removed more than 7600 gallons of gasoline trapped in soil (significantly more than the 6200 gallons estimated to be present), both above and below the water table, with separate-phase contamination extending to >120 ft deep. The maximum removal rate was 250 gallons of gasoline a day. The process was limited only by the ability to treat the contaminated substance at the surface. Actual field experience indicates that the process costs \$60–\$70 a cubic yard. Approximately 100,000 yd<sup>3</sup> were cleaned.

### Based on Three Technologies

Dynamic Underground Stripping relies on three integrated technologies; steam injection,

electrical heating, and underground imaging (Figure 4).

### Steam Injection

Steam is pumped into injection wells, heating the contaminated earth to 100°C. Steam drives contaminated water toward the extraction wells where it is pumped to the surface. When the steam front encounters contamination, volatile organic compounds are distilled from the hot soil and are moved to the steam/groundwater interface, where they condense. Vacuum extraction after full steaming of the contaminated zone continues to remove residual contaminants. The steam injection/vacuum extraction technique was developed at UCB (Udell and Stewart, 1989, 1990; Udell et al., 1991; Udell, 1994d). The steam system and operational design used here are described in Siegel (1994) and Udell (1994c). Predictive



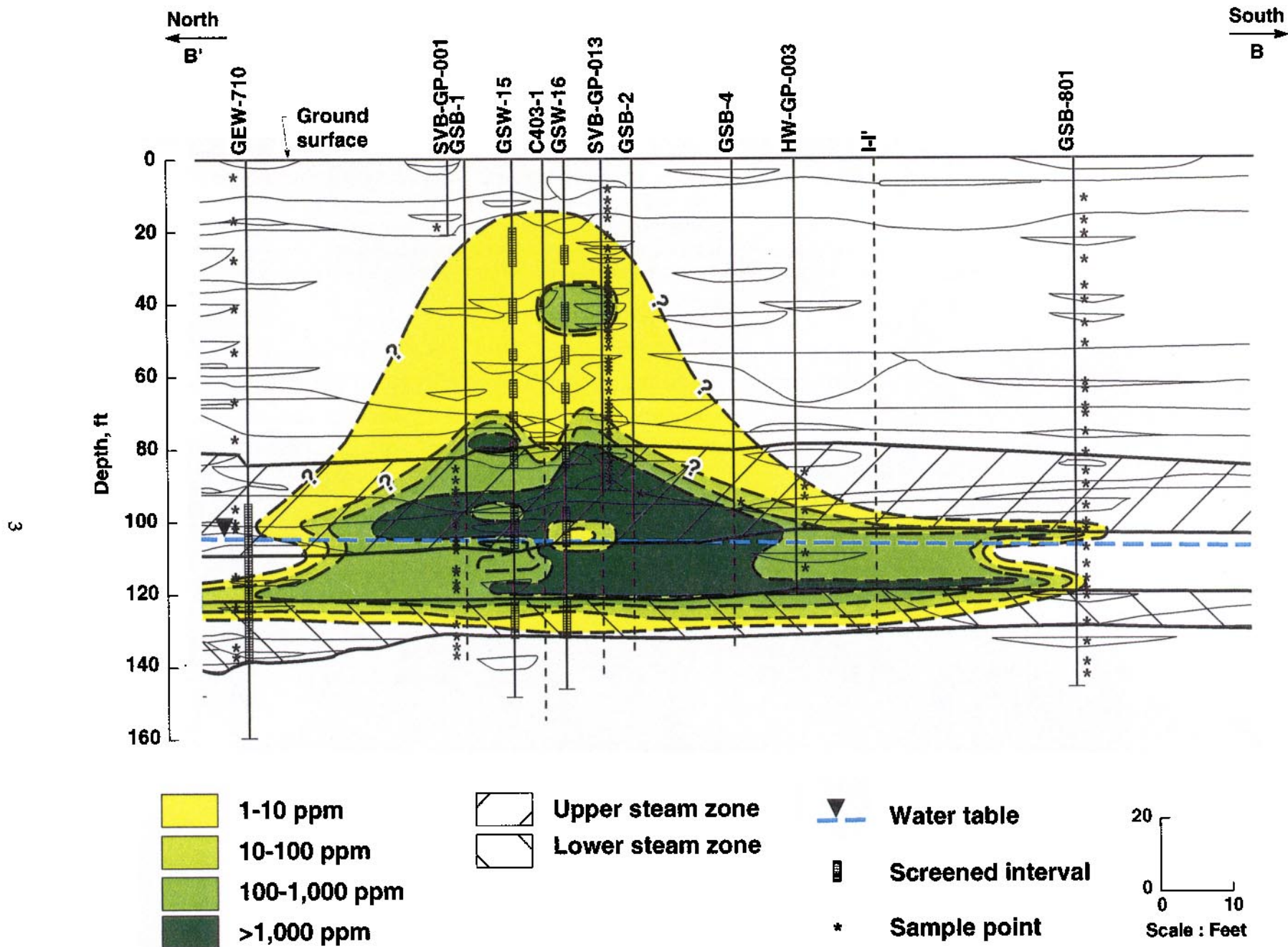


Figure 2. Cross section showing an approximation of the gasoline contamination at the treatment site before Dynamic Underground Stripping began. The darker areas represent higher concentrations; the darkest indicates free-product gasoline. The dashed line denotes the level of the water table. (From Bishop et al., 1994).

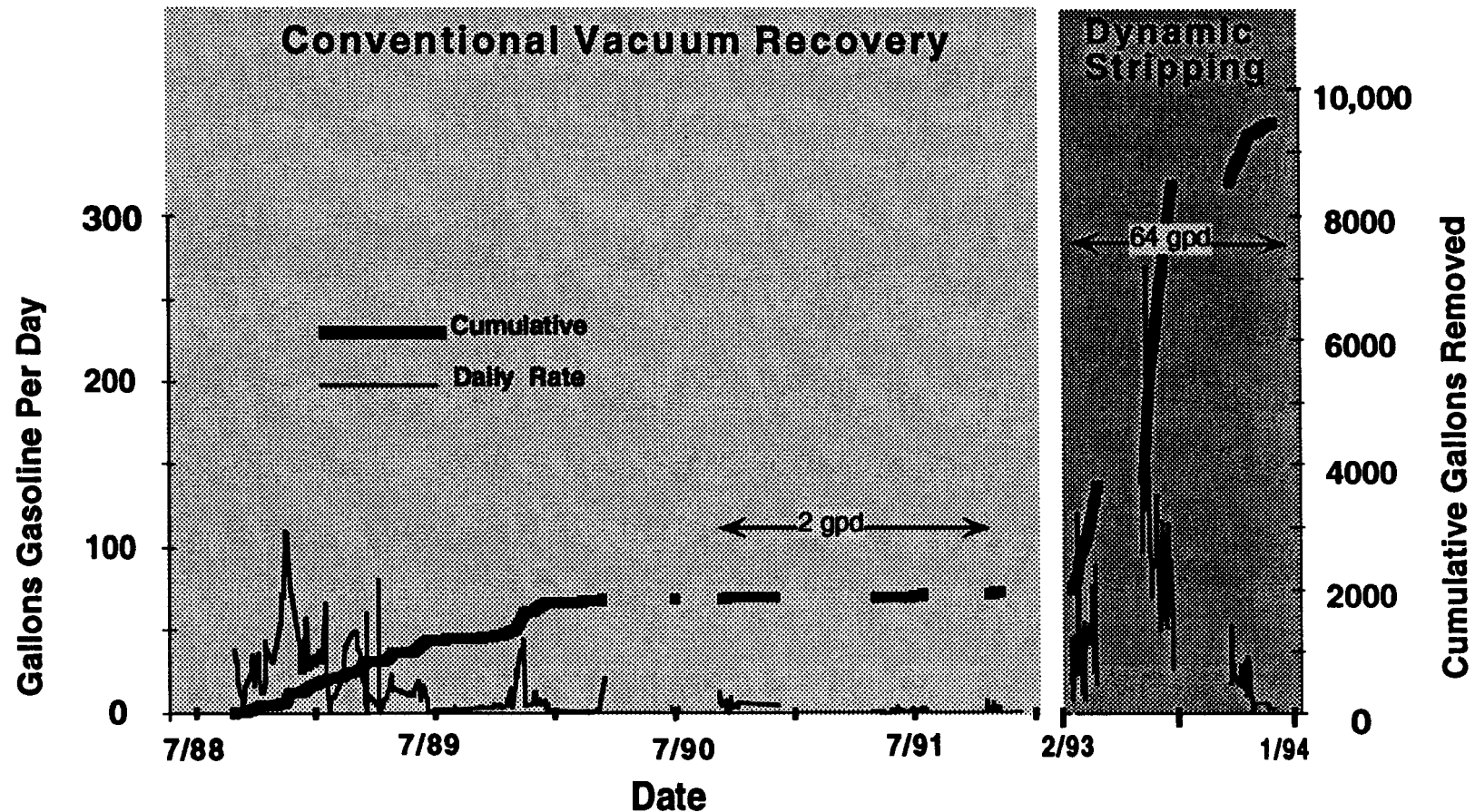


Figure 3. Recovery rates during Dynamic Underground Stripping compared to conventional methods fielded at the LLNL gasoline spill site. Vacuum extraction, begun in late 1988, stabilized at a recovery rate of 2 gallons of gasoline per day after an initially higher rate (Cook et al., 1991). Conventional pump and treat combined with vacuum extraction, tested just before the start of Dynamic Underground Stripping (not shown), showed an initial additional recovery rate of 0.5 gal/day gasoline in pumped water, for a total conventional recovery of 2.5 gal/day. Dynamic Underground Stripping averaged 64 gal/day during the year in which the 21 weeks of operations were conducted. Dynamic Underground Stripping removed vadose zone contamination at about 15 times the rate of conventional methods, and groundwater contamination at greater than 60 times the conventional rate.



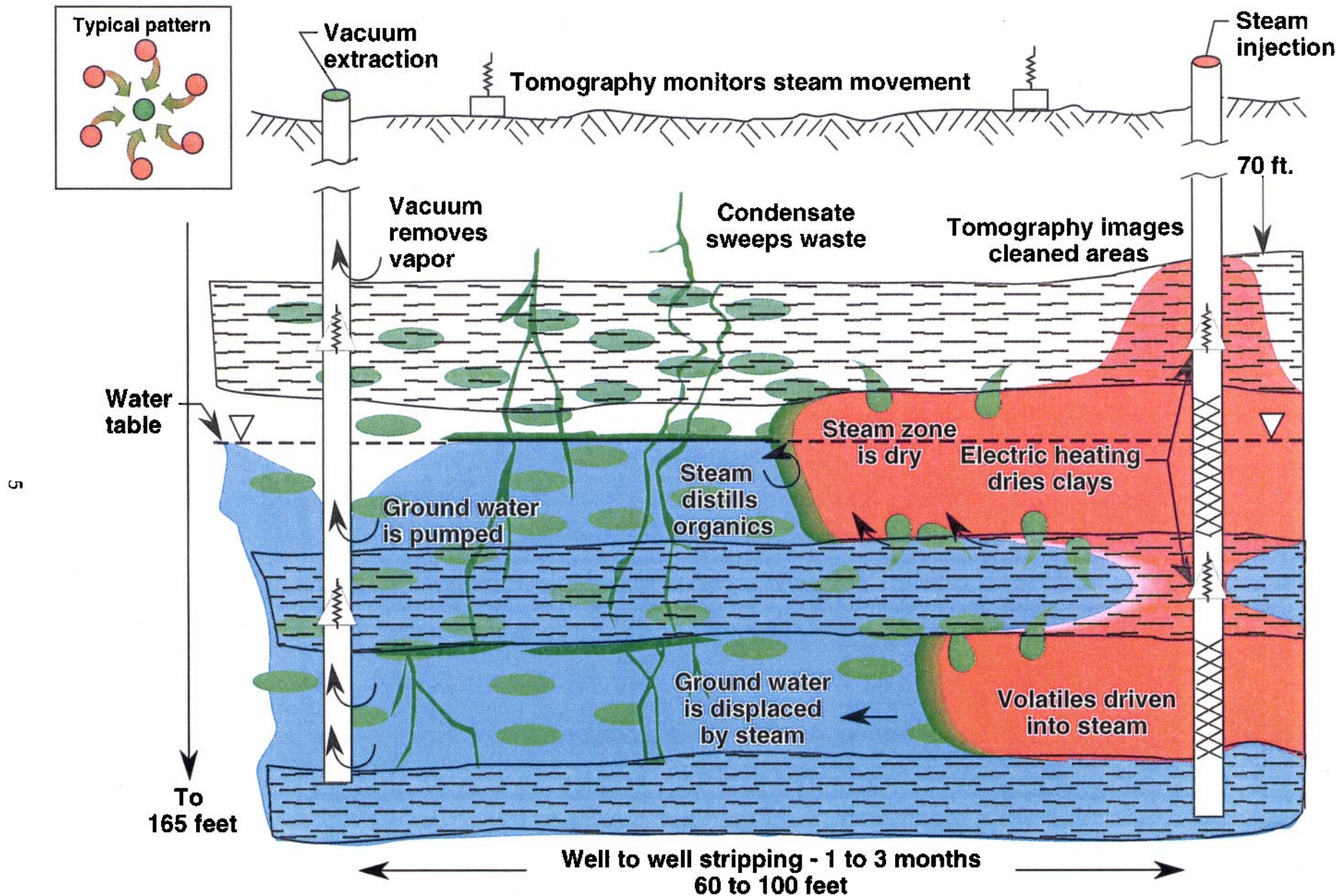


Figure 4. The Dynamic Underground Stripping process. Steam drives contaminated groundwater toward extraction wells and then heats the soil to distill organics. Electrical heating dries and distills impermeable clays that the steam cannot readily penetrate. Geophysical techniques monitor the process. The process operates both above and below the water table (dashed line) and is particularly economically attractive for free-product removal (solid green).

calculations of the operational characteristics and recovery efficiency of steam injection as applied at the LLNL gasoline spill site are given by Udell (1994b), Kenneally (1994), Adenekan and Patzek (1994), and Lee (1994).

### Electrical Heating

This technique heats clay and fine-grained sediments and causes water and contaminants trapped within the soils to vaporize and be forced into the steam-swept zones, where vacuum extraction removes them. Electrical heating is ideally suited for tight, clay-rich soil and/or near-surface (less than 20 feet) cleanups. It is an effective complement to steam injection, because it cleans the thick, less permeable zones that the steam does not penetrate well.

Electrical heating has been used in a number of configurations in enhanced petroleum recovery (e.g., Chute et al., 1987; Chute and Vermeulen, 1988); the three-phase system used here was designed at LLNL (Buettner and Daily, 1994a; McGee et al., 1994). Details of the electrical heating construction and operational design used here are given by Siegel (1994), and the results of the preheat phase are found in Buettner and Daily (1994b). Our predictive and diagnostic

modeling capability for electrical heating is presented by Carrigan and Nitao (1994). Sweeney et al. (1994) give details of the post-steam electrical heating process conducted during this experiment.

### Underground Imaging

To monitor the Dynamic Underground Stripping process, we used geophysical imaging methods to map the boundary between the heated zones and the cooler surrounding areas. Electrical resistance tomography (ERT) has proven to be the best imaging technique for near-real-time images of the heated zones (Newmark, 1992, 1994c; Ramirez et al., 1993; Vaughn et al., 1993). This technique is necessary for controlling the thermal process and for monitoring the water movement. Details of the use of ERT at the gasoline spill site are given by Newmark (1994b), and Ramirez et al. (1994). Tiltmeters provided additional information regarding the shape of the steamed zone (Hunter and Reinke, 1994), while detailed temperature and geophysical logs provided extremely accurate assessments of the degree of penetration and the complex heating of the numerous heterogeneous formation layers (Newmark, 1994b; Goldman and Udell, 1994; Boyd et al., 1994).

## The LLNL Gasoline Spill Site

We conducted an experimental application of the Dynamic Underground Stripping technique during 1993 at the LLNL gasoline spill site. This is the former site of the Laboratory's filling station; fueling operations at this location date back to the 1940s, when the LLNL site was a U.S. Naval air station. It is located in the center of an industrial area—the Laboratory's shipping and receiving yard. A county road runs along the south side, and major underground utility lines run through the site.

Previous characterization results were combined with an extensive set of measurements taken during the installation of 22 process and monitoring boreholes at the site. Details of the site characterization are given in Bishop et al. (1994). This characterization showed that an estimated 6200 gallons of gasoline were present within our target treatment area (both above and below the water table) (Figure 2). Gasoline was trapped up to 30 ft below the water table because of a rise in the water table after the spill occurred, with the gasoline held below water by

capillary forces in the soil. The soils at the site are alluvial, ranging from very fine silt/clay layers to extremely coarse gravels, with unit permeabilities ranging over several orders of magnitude. There are two principal permeable zones, one above and one below the water table, which is located at 100 ft. In between the permeable zones, straddling the water table, is a 10–15-ft-thick silty/clay layer of low permeability, which was also heavily c

aminated (Nelson-Lee, 1994). The targeted volume was intended to all of the free-phase gasoline at the site, a distorted cylinder about 120 ft in diameter and 100 ft high, extending from a depth of 60 ft to a depth of 140 ft (Figure 5). Later results indicated that two small areas of gasoline probably existed outside the treatment area, possibly from separate spills.

Six steam injection/electric-heating wells were placed to surround the free product in an irregular circle determined by the shape of the free product; three additional electric heating wells were placed near the center of the spill. These were not part of the original design, but



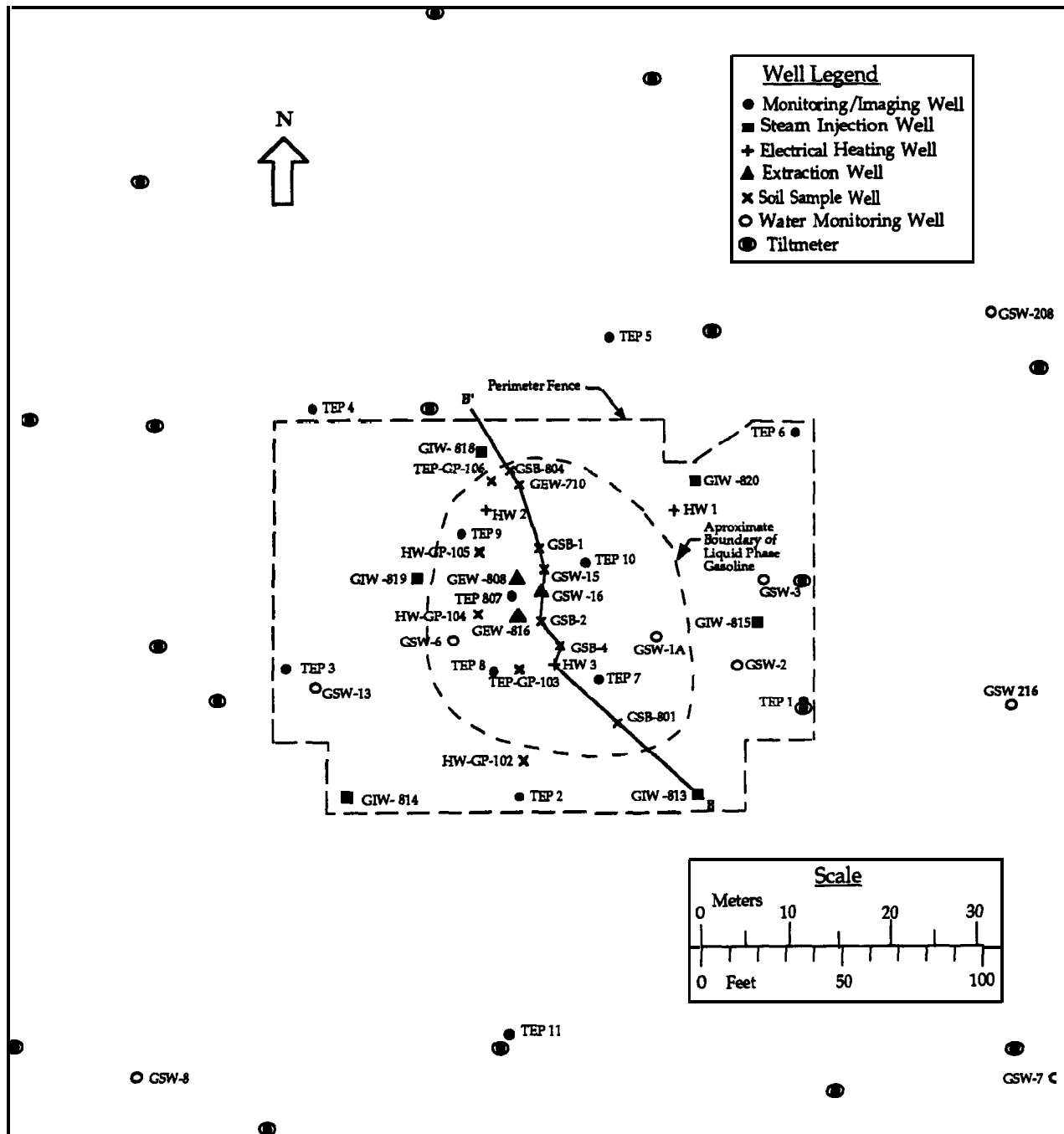


**Figure 5. Aerial view of the LLNL gasoline spill area, showing regions of known or suspected free-product gasoline contamination (circled). The area is within the LLNL shipping and receiving yard. East Avenue, a county road, is seen on the south edge of the photograph. Injection wells were sited to encircle the central plume of free product to ensure that the gasoline would be moved toward the extraction well cluster at the center.**



were required when the free-product zone was discovered to be larger than anticipated during the drilling of the injection wells. Each injection well was initially center-punched with a small-diameter hole for characterization. The discovery of unexpected free product in two of them had

minimal impact; the holes were completed as monitoring locations, and new injection wells were drilled farther from the spill center. We placed eleven monitoring/imaging wells within and outside the target area to provide control of the heating processes (Figure 6).



**Figure 6. Map of the LLNL gasoline spill site, showing the location of wells referred to in this summary. The location of cross section B-B' (Figure 2) is shown. (Not all pre-Dynamic Underground Stripping well and boring locations are shown.) This map shows a slightly larger area than Figure 5.**